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NRL Memorandum Report 6531

AD-A212 707

## Cold Tests of Quasi-Optical Gyrotron Resonators

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September 7, 1989

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 6531			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory		6b. OFFICE SYMBOL (If applicable) Code 4794		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000			7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION DOE		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20545			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
					WORK UNIT ACCESSION NO. DN780-307
11. TITLE (Include Security Classification) Cold Tests of Quasi-Optical Gyrotron Resonators					
12. PERSONAL AUTHOR(S) Fischer, R.P., Hargreaves,* T.A. and Fliflet, A.W.					
13a. TYPE OF REPORT Interim		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 1989 September 7	
				15. PAGE COUNT 31	
16. SUPPLEMENTARY NOTATION *Mission Research Corp., Newington, VA 22122					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Quasi-optical gyrotron		
			Cold tests		
			Quality factor		
			Open resonator		
			Scalar diffraction theory,		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Cold tests are performed on a number of quasi-optical gyrotron resonators at 94 and 120 GHz to determine the variation of cavity Q with mirror separation. The separation between the resonator mirrors is varied between 15 and 35 cm, with measured quality factors ranging from 10,000 to 100,000. Good agreement is obtained between the measured data and values calculated from scalar diffraction theory. The effect of misaligning the mirrors is also examined experimentally.</p>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS				21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL Richard P. Fischer				22b. TELEPHONE (Include Area Code) (202) 7673765	
				22c. OFFICE SYMBOL Code 4794	

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# COLD TESTS OF QUASI-OPTICAL GYROTRON RESONATORS

## I. Introduction

Gyrotrons are currently under development as efficient, high-power sources of millimeter waves. The trend is toward higher power ( $> 1$  MW average) and higher frequency (submillimeter wavelengths). Waveguide cavity gyrotrons are presently the leading candidate for electron cyclotron heating of fusion plasmas.<sup>1</sup> However, these conventional cavity gyrotrons suffer from large ohmic heating, transverse mode competition, and electron beam collection problems as power and frequency are increased. The quasi-optical gyrotron (QOG) was proposed by Sprangle, Vomvoridis, and Manheimer in 1980<sup>2,3,4,5</sup> and has the potential to overcome each of these difficulties.

The quasi-optical resonator is comprised of a pair of spherical mirrors separated by many wavelengths. The QOG operates in a series of  $TEM_{00l}$  modes, where  $l > 100$  for cw relevant configurations. Higher order transverse modes can be made to suffer from large diffraction losses due to the finite size of the mirrors. The diffraction of the  $TEM_{00l}$  modes around one or both of the mirrors is collected as output.

Typical round-trip diffraction losses are several percent. This output coupling sensitively depends upon the mirror size, radius of curvature, and separation. For a given pair of mirrors, output coupling is increased by increasing the separation between the mirrors. However, the radiation waist near the center of the cavity is relatively insensitive to changes in separation. Thus, the output coupling can be varied independently with respect to the interaction length. This is a unique feature of the QOG, and is quite advantageous experimentally.

The electron beam direction is perpendicular to the axis of the resonator, which allows the beam to be collected separately from the radiation. This is an important feature for high-power devices and eases restrictions on the collector. It also facilitates the use of depressed collector technology. The cavity mirrors are well removed ( $> 10$  cm) from the wave/beam interaction region, which reduces the ohmic heating density at the mirrors.

The quality factor ( $Q$ ) of a resonator is an important parameter which describes how well the cavity stores energy and is closely related to the output coupling. The  $Q$  for a

Fabry-Perot-type resonator can be very large. Quality factors on the order of 100,000 are typical for resonators used in recent experiments at the Naval Research Laboratory. Since the balance between ohmic effects and diffraction is very important in the QOG, a detailed experimental study is called for.

Fabry-Perot resonators have been used for years to measure the microwave properties of solids, liquids, and gases.<sup>6</sup> These cavities have proven to be quite useful. For permittivity and loss measurements, the design goal is to make the  $Q$  as large as possible. This is accomplished by making the mirrors large so that diffraction losses are negligible. Energy is typically coupled into the cavity through coupling holes or a dielectric beam splitter.

Cold tests of gyrotron cavities are difficult to perform in practice. Most cold-test schemes involve drilling coupling holes into the cavity walls,<sup>7</sup> which can perturb the cavity mode severely. It is also difficult to couple efficiently to the mode of interest, which is frequently a high-order mode. Woskoboinikow *et al.*<sup>8</sup> radiated their conventional gyrotron cavities in the far field and analyzed the reflected signal. This technique has the advantage of being nondestructive, so that the hot test cavity may be used for the cold test. It is difficult to test a QO cavity this way because little energy is coupled into the resonator mode.

Although the QOG is an advanced concept, it operates in the fundamental Gaussian mode. This makes coupling to the correct mode very easy. This study uses the method of Perrenoud *et al.*<sup>9</sup> where a small hole is used to couple energy into the resonator and diffracted power is collected with a standard gain horn as output. This technique has a distinct advantage in that there is no background radiation pattern on the oscilloscope trace, which increases the accuracy of the measurement. The majority of the measurements in this article concern the variation of  $Q$  with separation for various cavities. Good agreement is obtained between measured values and calculations based on scalar diffraction theory. The effect of misaligning the mirrors is also examined experimentally.

## II. Quasi-Optical Resonators

The  $Q$  of a Fabry-Perot-type resonator can be written

$$Q = \frac{4\pi L}{\lambda f_L} \quad (1)$$

where  $L$  is the separation between mirrors,  $\lambda$  is the free-space wavelength, and  $f_L$  is the fractional round-trip loss. In practice, this loss factor includes ohmic losses, diffraction losses, and losses due to coupling holes. These are the three loss mechanisms which are important in this study. The total  $Q$  of the resonator can be expressed as

$$\frac{1}{Q} = \frac{1}{Q_\Omega} + \frac{1}{Q_{d,c}} \quad (2)$$

where  $Q_\Omega$  is the ohmic  $Q$ , and  $Q_{d,c}$  is the  $Q$  due to diffraction and coupling losses. The ohmic  $Q$  is calculated using the formula

$$Q_\Omega = \frac{L}{4}(f\pi\mu_0\sigma)^{\frac{1}{2}}. \quad (3)$$

In this expression,  $\mu_0$  is the permeability of free space and  $\sigma$  is the conductivity of the mirrors. Silver- and gold-plated mirrors are used in the cold tests, with conductivities  $6.15 \times 10^7$  and  $4.5 \times 10^7$  Siemens/m, respectively. The ohmic  $Q$  increases linearly with separation and is unimportant for large output coupling.

The diffraction/coupling  $Q$  is calculated separately from the ohmic  $Q$ . This is accomplished by a computer code which is based on a scalar Huygen's formulation.<sup>10</sup> Inputs to the code include the wavelength of the radiation, the mirror radius, the radius of curvature of the mirrors, the separation between the mirrors, and the dimensions of a coupling hole. Some of these parameters are illustrated in Figure 1. The program also models cavities where the mirrors are not identical. Outputs from the code include  $Q_{d,c}$ , the balance between  $Q_d$  and  $Q_c$ , and the electric field distribution along the surface of each mirror for the  $TEM_{00}$  and  $TEM_{01}$  modes. Other modes may also be analyzed.

A chief obstacle to performing cold tests of millimeter-wave resonators is coupling power into the cavity without perturbing the  $Q$  too seriously. In this study, a small coupling hole

is drilled through the center of one mirror. The size of the hole is chosen to minimize degradation of  $Q$  while coupling a meaningful amount of power into the cavity. The radius of the coupling hole is 0.38 mm. The calculated effect of the coupling hole can be seen in Figure 2. For separations greater than 20 cm, there is practically no difference between the two resonators. In the present Naval Research Laboratory QOG experiment, the separation can be varied between 20 and 28 cm. This resonator lies well within the confocal instability point at 38.7 cm separation and the concentric stability limit at 77.4 cm separation. Thus, this cold test cavity should be a good model for the experiment. Below 20 cm, any change in the round-trip losses results in a large change in the total  $Q$ , due to the small output coupling. Figure 3 shows the round-trip transmission loss due to diffraction as a function of separation for the cavity analyzed in Figure 2. The transmission varies between 2.5% to 6% in the range of interest.

### III. Cold Test Apparatus

The experimental set-up is similar to that adopted by Perenoud *et al.*<sup>9</sup> A schematic diagram is shown in Figure 4. The entire arrangement is located on an optical table, with the quasi-optical mirrors mounted on six-inch diameter optical mounts which can be translated by hand on a rail.

A 0.76-mm diameter coupling hole pierces the left mirror. It is counterbored from behind, leaving a .005- to .010-inch wall. A WR-8 waveguide is inserted from the back of the coupling mirror for input, while a standard gain horn intercepts a small amount of the diffracted signal as output. In practice, the pick-up horn is placed next to the coupling mirror so that it may remain stationary while the far mirror is translated.

Two millimeter-wave sources are used for the measurements. The first is a 94 GHz IMPATT which produces 20 mW of power. Its frequency is swept by applying a 1-volt ramp to the FM port. The second source is a 120 GHz reflex klystron with a power output of several milliwatts. It is also swept with a low-voltage ramp, which is amplified in the klystron power supply/modulator and applied to the reflector. It is desirable to have a

linear frequency sweep versus time for the millimeter-wave source. This allows for direct measurement of the full width at half maximum ( FWHM) from the oscilloscope with no corrections. Typical sweeps are 20 MHz for this work and are linear over the range of interest for most resonators.

A detector/amplifier manufactured by Millitech Corp., which has a sensitivity of 50 V/mW, is used to observe the small signals collected by the radiation pick-up. The detector and its power supply are shielded, which reduces the noise on the oscilloscope to 0.1 mV. Typical resonances observed on the oscilloscope are 1-2 mV. The horizontal trace is calibrated using the interferometer in Figure 4. The interferometer is comprised of two six-inch diameter mirrors and has a  $Q$  of approximately 70,000. The separation can be varied between 32 and 43 cm, with fine adjustments facilitated by a micrometer graduated to 0.0001 inches. The interferometer would not be required if the quasi-optical cavity was mounted with a precision micrometer.

The resonator mirrors are made of oxygen-free, high-conductivity (OFHC) copper. They are machined, polished, and then plated with either silver or gold. The surface finish is  $\lambda/20$  for  $\lambda = 10\mu\text{m}$ . Thus, surface scattering of millimeter waves should be negligible. The mirrors have a 0.5-mm bevel at the mirror's edge, which decreases the effective diameter by 1.0 mm.

A unique feature of the cold test arrangement is that the resonator mirrors are aligned with an HeNe laser. The incident beam defines the axis of the resonator, so that the mirror angle can be optimized by aligning the reflected and incident beams. The coupling hole is used to full advantage by passing the beam through the hole for centering and alignment. The resonator mirrors can be quickly aligned to better than  $\frac{1}{10}^\circ$ .

## IV. Results

Figure 5 shows measured and calculated values of  $Q$  versus separation for a resonator with 4.6-cm diameter mirrors. The coupling hole is 0.76 mm in diameter and the frequency is 120 GHz. The radius of curvature is 38.7 cm for each of the mirrors used in this work.



The agreement between data and theory is quite good for separations greater than 20 cm, which is the region of operation the QOG. Measured values are somewhat higher than predicted at closer separations. This discrepancy may be due to the coupling hole.

A second set of measurements is shown in Figure 6. The frequency is 94 GHz, the resonator mirrors are 5.6 cm in diameter, and the coupling hole is 0.76 mm in diameter. The agreement between measured and calculated values is quite good. This resonator is similar to the resonator in Figure 5 in terms of  $Q$ .

Figure 7 shows data obtained with the 4.6-cm mirrors measured at 94 GHz. The values for  $Q$  are much lower due to increased diffraction losses at the longer wavelength. A  $Q$  of 7,000 corresponds to a round-trip transmission coefficient of 18% for a separation of 26 cm.

The present QOG utilizes a symmetric cavity; the mirrors are identical. Future configurations may include asymmetric resonators which couple power from one side only. Figures 8 and 9 show measured and calculated  $Q$ 's for slightly asymmetric cavities. There is diffraction around both mirrors, with more loss from the smaller mirror. The code accurately predicts the properties of these asymmetric cavities.

Another valuable measurement is the effect of misaligned mirrors on the  $Q$ . Perrenoud *et al.*<sup>9</sup> found that  $0.5^\circ$  tilt resulted in a 50% degradation of  $Q$  for their configuration. This information is important because the mirrors must be attached to the magnet dewar, and it is difficult to estimate how well the dewar flanges are aligned. Figure 10 shows the effect of mirror misalignment on  $Q$  for one of the asymmetric cavities. The mirror separation is 15.8 cm and the frequency is 94 GHz. The  $Q$  begins degrading after  $1^\circ$  of misalignment. By  $2^\circ$ , the  $Q$  is reduced by 20%. The small scatter of the data for tilts less than  $1^\circ$  is indicative of the reproducibility of the measurement. In general, the sensitivity of the resonator to misalignment depends upon mirror size and separation. Increasing the separation to 25 cm has little effect on sensitivity to alignment for this cavity.

There are several sources of error in these measurements of  $Q$  versus separation. If the frequency sweep is not perfectly linear in time, a systematic error will be present. Secondly, there is a random error in reading the FWHM from the oscilloscope. A third source of error

is due to the slightly asymmetric shape of the resonance on the oscilloscope. Adjusting the pick-up horn usually corrects this problem. Hence, the measured values should be accurate to better than  $\pm 10\%$ . This error can be lowered to below  $\pm 5\%$  with calibration and careful technique.

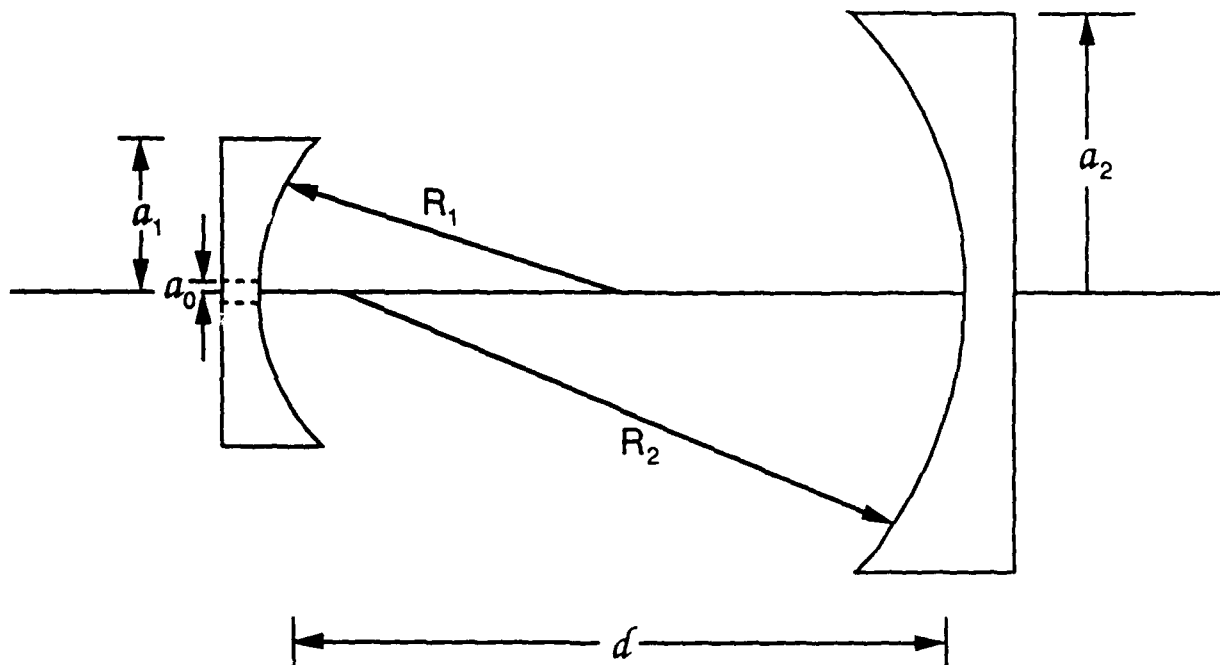
## Acknowledgements

This work was supported by the Office of Fusion Energy of the Department of Energy and the Office of Naval Research.

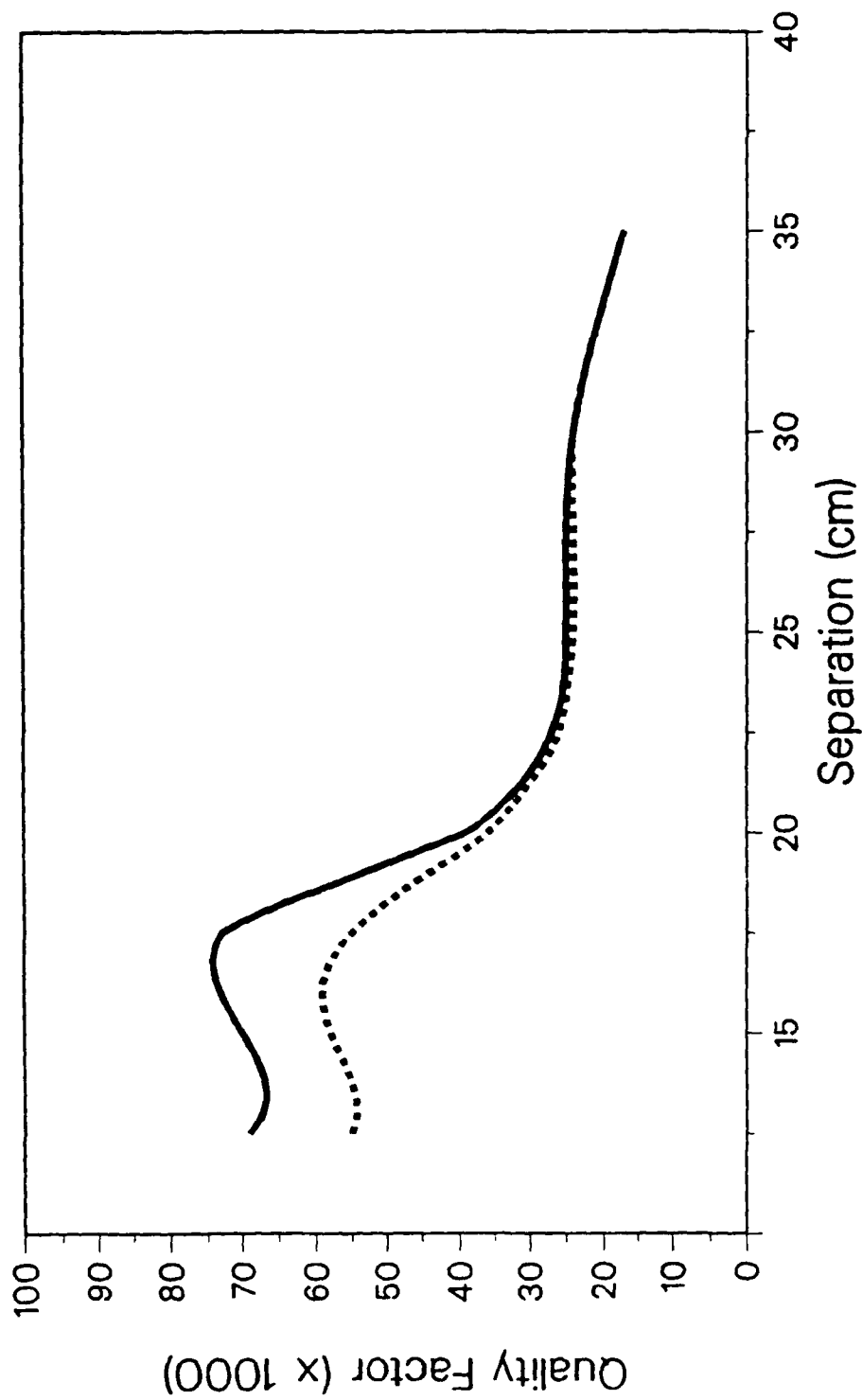
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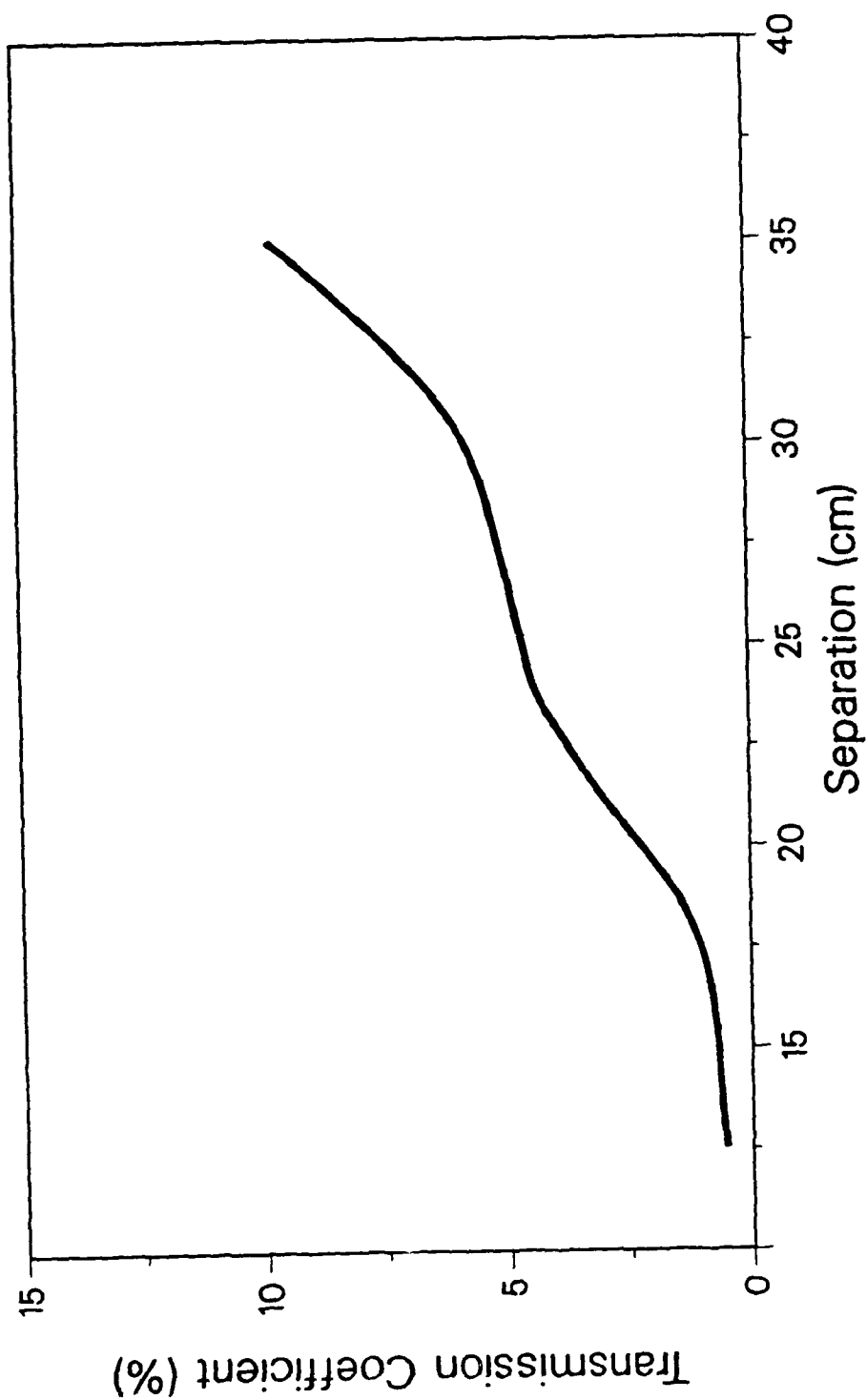
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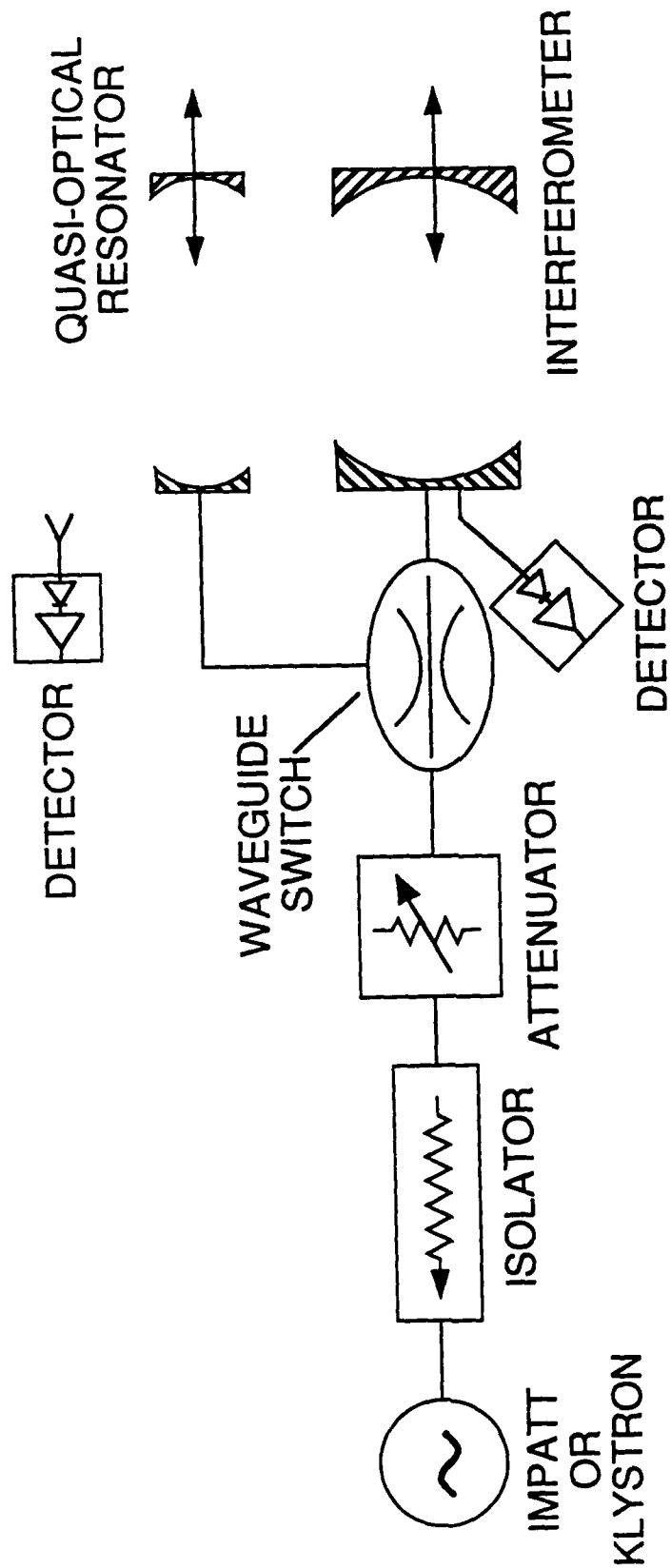
**Figure 1** Cross section of a quasi-optical resonator showing two different sized mirrors with a hole for input coupling.



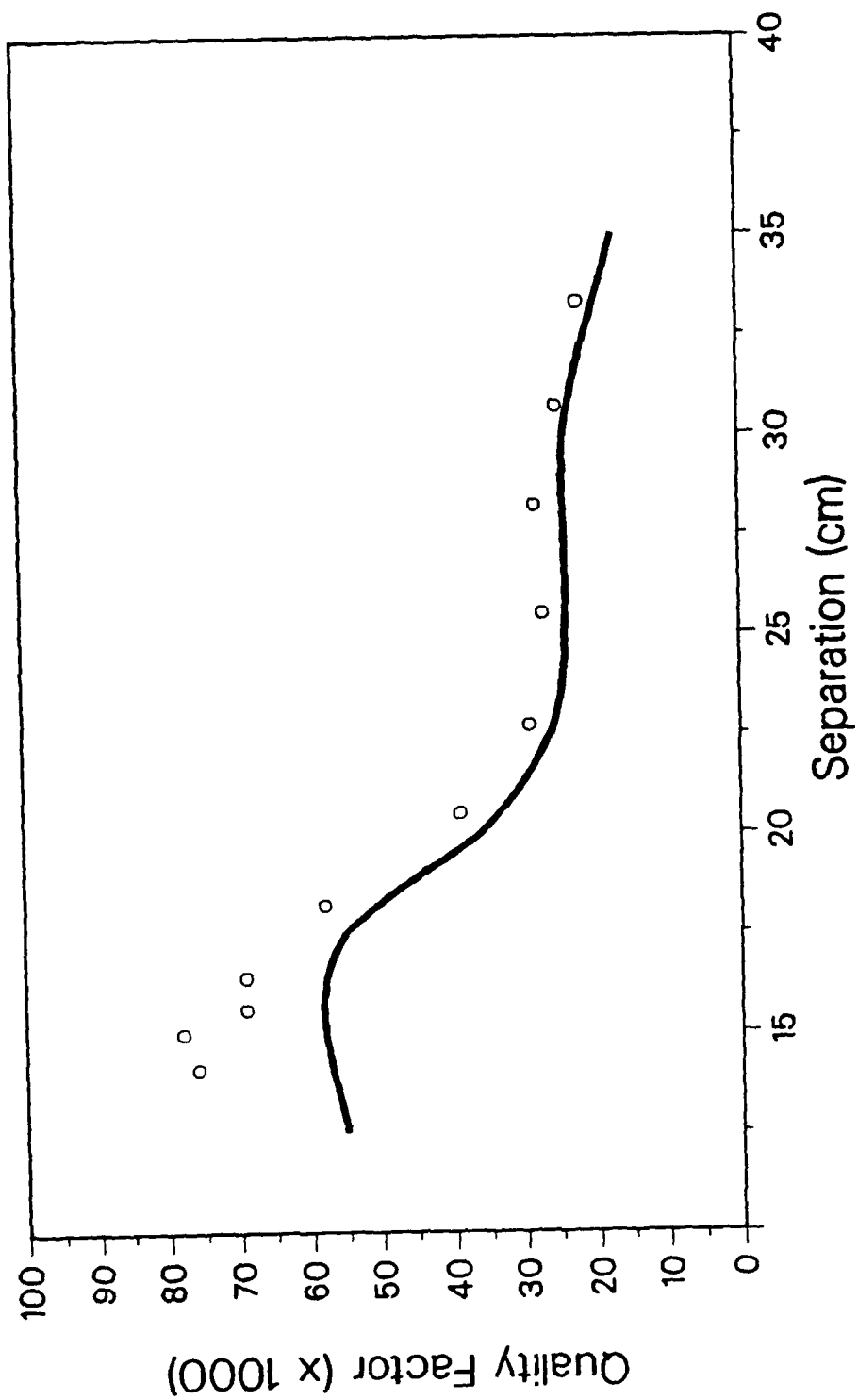
**Figure 2** The calculated effect of a coupling hole on the cavity Q. The solid curve is the resonator without the hole; the dashed curve is for a cavity with a 0.76-mm diameter coupling hole (frequency = 120 GHz, mirror diameter = 4.6 cm, radius of curvature = 38.7 cm).



**Figure 3** Round-trip transmission coefficient versus mirror separation (frequency = 120 GHz, mirror diameter = 4.6 cm, radius of curvature = 38.7 cm). The separation is typically varied between 20 and 28 cm in the QOG.

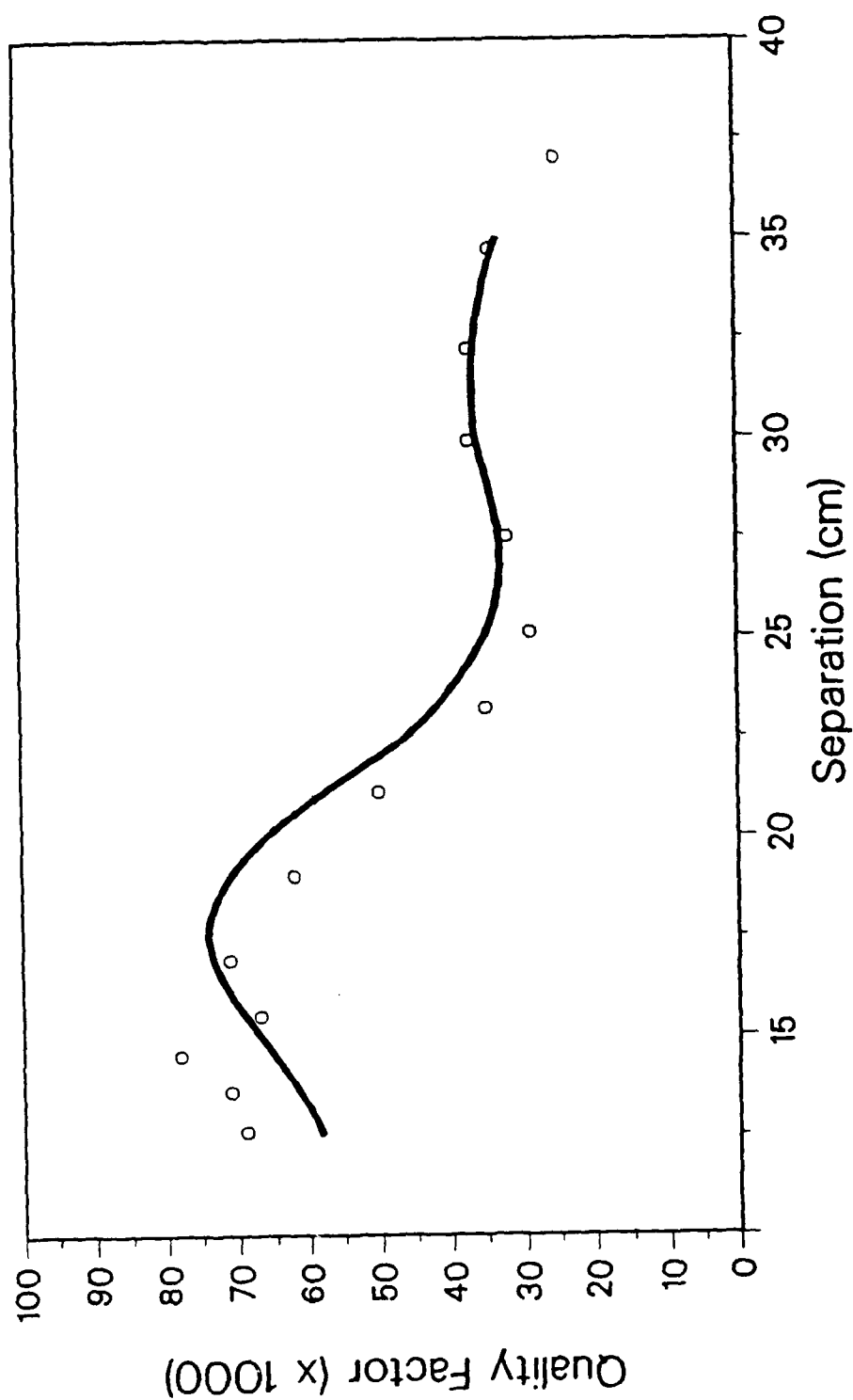


**Figure 4** Schematic diagram of the cold-test apparatus. Output is collected as diffraction around one of the quasi-optical mirrors.

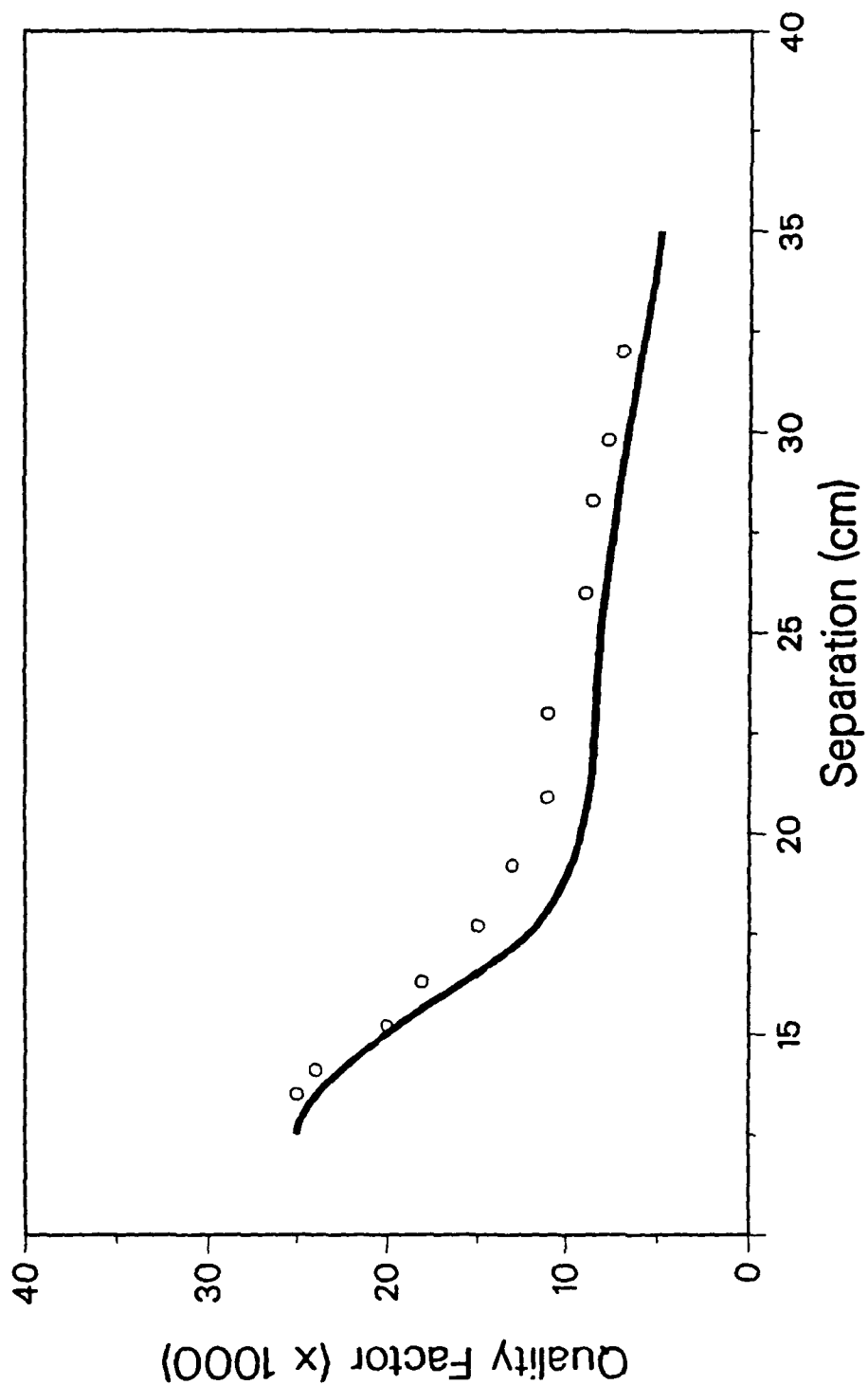


**Figure 5** Measured (open dots) and theoretical values (solid curve) of cavity  $Q$  versus mirror separation (frequency = 120 GHz, mirror diameter = 4.6 cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).

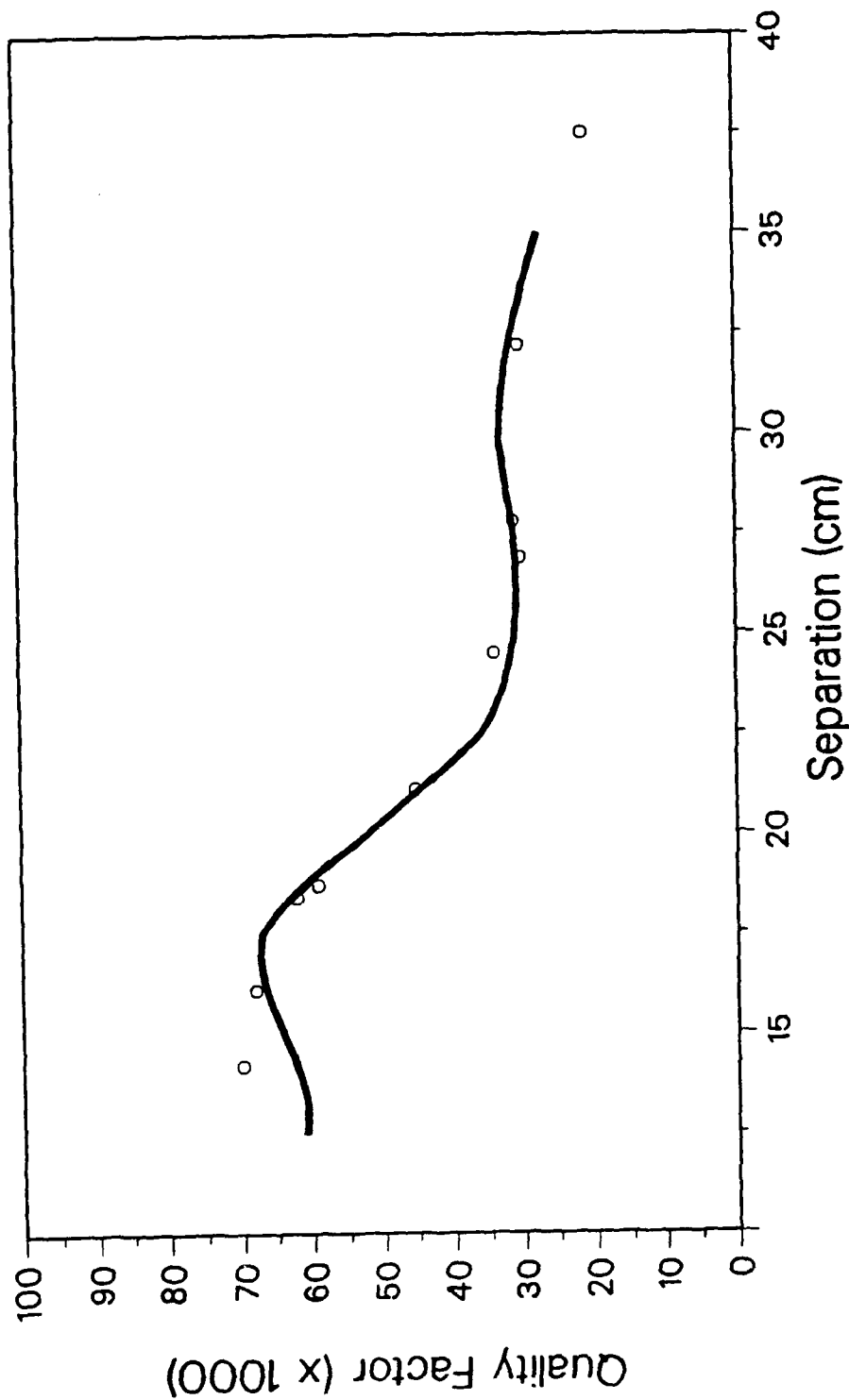




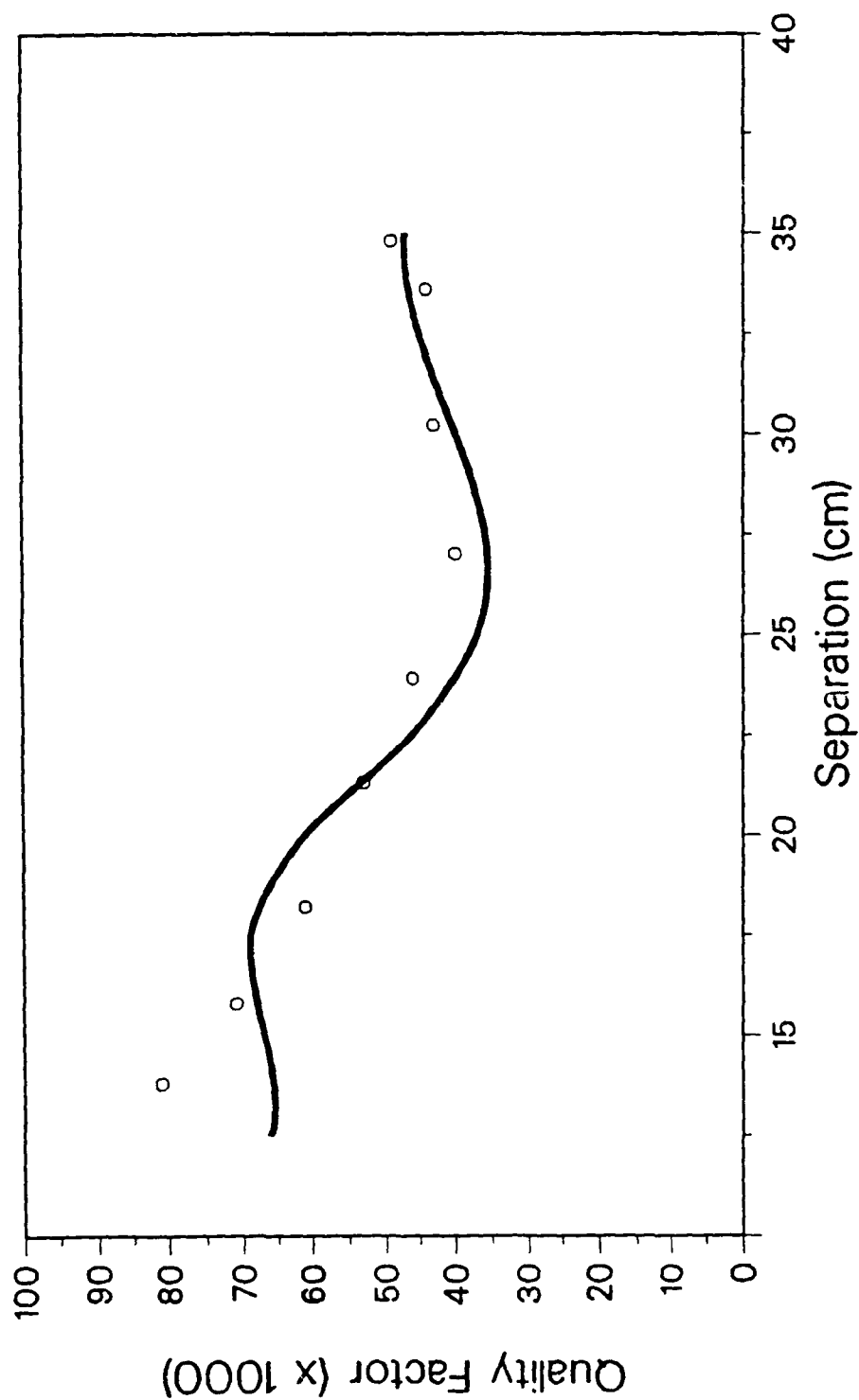
**Figure 6** Measured (open dots) and theoretical value (solid curve) of cavity Q versus separation (frequency = 94 GHz, mirror diameter = 5.6 cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).



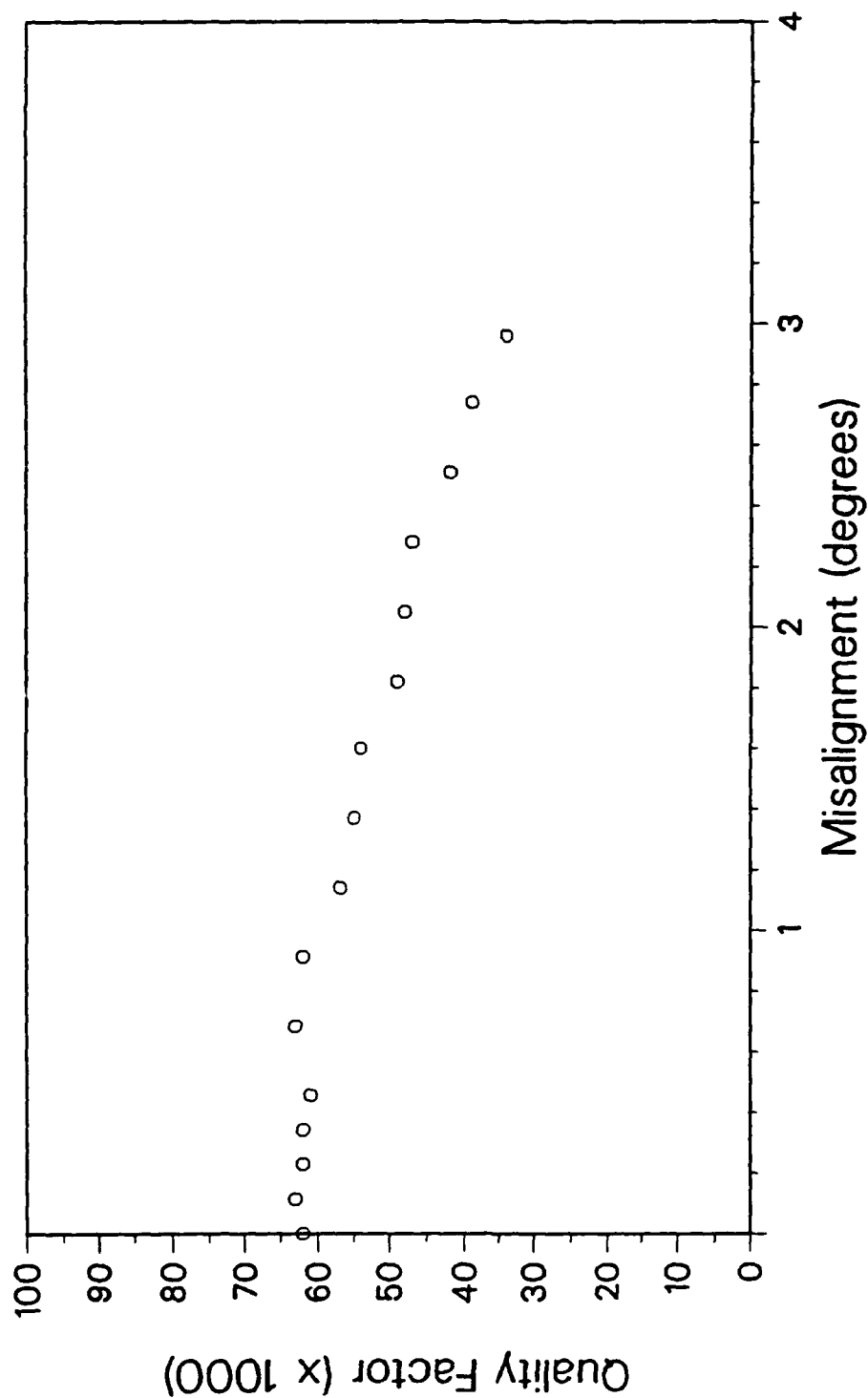
**Figure 7** Measured (open dots) and theoretical values (solid curve) of cavity Q versus separation (frequency = 94 GHz, mirror diameter = 4.6 cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).



**Figure 8** Measured (open dots) and theoretical values (solid curve) of cavity  $Q$  versus separation for an asymmetric resonator (frequency = 120 GHz, mirror 1(2) diameter = 4.6(5.0) cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).



**Figure 9** Measured (open dots) and theoretical values (solid curve) of cavity  $Q$  versus separation for an asymmetric resonator (frequency = 120 GHz, mirror 1(2) diameter = 4.6(5.6) cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).



**Figure 10** Cavity  $Q$  versus mirror misalignment (frequency = 94 GHz, mirror 1(2) diameter = 5.0(5.6) cm, radius of curvature = 38.7 cm, hole diameter = 0.76 mm).

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